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**A PORTABLE FETAL HEART MONITOR AND ITS ADAPTION
TO THE DETECTION OF CERTAIN PRENATAL
ABNORMALITIES**

By

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OBJECTIVES

There were three primary objectives for this task:

1. The investigation of the feasibility of making the fetal heart rate monitor portable, using a laptop computer.
2. Improvements in the signal processing for the monitor.
3. Implementation of a real-time hardware software system.

These tasks have been completed as discussed in the following section.

ACCOMPLISHMENTS

Hardware and software for a portable acoustic fetal heart-rate monitor has been developed and tested. Both the hardware and algorithms implemented in software are substantial improvements over previous versions. Particular attention has been paid to implementing options which will enable ongoing clinical testing to be used to evaluate and improve the system. For example, one mode of operations allows data to be simultaneously gathered from the acoustic unit and a commercial ECG based unit for detailed comparisons. In this report we briefly summarize the hardware, the algorithms, the implementation, and the results of tests conducted to date.

1. The hardware

The first part of the front-end electronics consists of 14 low-noise high-gain ($\times 100$) instrumentation amplifiers (AD524). Each amplifier is connected to a single sensor from one differential sensor pair. The two signals obtained from the two sensors of each sensor pair are then added, using a differential gain factor selected to reduce the effects of motion artifacts. Each of the 7 resultant signals is then bandpass filtered (3rd order highpass @ 10 Hz followed by a 6th order Butterworth lowpass at 55 Hz). These signals are then time-division multiplexed to 2 channels, to allow simultaneous sampling of all 7 signals. An adjustable gain amplifier follows the multiplexor.

The seven signals are converted to digital data using the two AD channels (16-bit) on a TMS320C31 based DSP card (ELF card from Atlanta Signal Processors Inc.) The effective sampling rate is 2000 Hz for each channel. The ELF card is used for signal processing, as described below. The ELF card is housed in a portable PC which is used for graphics display, user interface, and saving of acoustic data and fetal heart rate information.

2. The algorithm for measuring fetal heart rate

Each of the 7 sensor signals is decimated to 500 Hz, digitally filtered with a 75th order linear phase FIR digital bandpass filter (passband of 16 Hz to 38 Hz), and further decimated to a 250 Hz sampling rate. Note that the use of digital filters for a significant portion of the filtering allows for great flexibility, since these filters are very easily changed, and can easily be tailored to any reasonable desired response. The linear phase property also insures minimal waveform distortion. After filtering, fetal heart rate is computed independently using two methods from each of the seven signals. In the first method, the nonlinear Teager Energy operator is applied to the signal, to highlight regions of high energy (i.e., the heart beats). This signal is then analyzed with an autocorrelation operation to determine an estimate of the heart rate. In the second method, the autocorrelation method is used directly on the filtered acoustic signal. Thus a total of 14 heart rate estimates are made. These estimates are ranked using a figure of merit, which is derived from continuity constraints and a measure of periodicity in the waveform. The highest ranking estimate is then used as the heart rate for that frame of data. The entire process is repeated every .5 seconds.

A very important consideration in the monitor is to maintain the best possible signal-to-noise ratio. Therefore particular attention was paid to matching the signal level to the dynamic range of the AD convertors. A useful feature is that the input range of the A-D convertor is software adjustable from $\pm .21$ volts to ± 2.8 volts (a range of 22.5 dB). Therefore in one mode of operation the rms value of each sampled signal is used to control this AD range to match the measured signal level. An implicit assumption is that the rms level does not change rapidly. These calculations are based on a 10 second window. Alternatively, in a "manual" mode, the user selects the AD range and this is no longer automatically adjusted.

3. The software system

The software was developed in C code. There are two major modules for the code--code which run on the host PC and code which runs on the DSP processor board. The PC code was developed using Microsoft C V7.0. The DSP code was developed using the Texas Instruments C compiler and calls to the SPOX real-time DSP operating system. There are several options, and multiple suboptions within each.

The primary options are:

1. Acoustic unit only
2. Acoustic unit + ECG unit
3. One channel oscilloscope
4. Seven channel oscilloscope
5. ECG unit only

These options are displayed on a menu which appears when the program is started. We next briefly describe each of these options.

Acoustic unit only

This is the primary mode used with the monitor. If this mode is used, a strip chart type recording is drawn on the computer screen. There are two strips, each depicting up to 9 minutes of rate information. In real-time, as the heart rate is computed, it is drawn on the screen. The rate is drawn in green if the figure of merit (as mentioned above) is above an empirically determined threshold. Otherwise it is drawn in yellow. The rate also appears as a numerical value on the bottom of the screen. If a recording longer than 18 minutes is made, the tracing is redrawn on the oldest part of the data.

The user has several options in this mode. First manual or automatic mode can be selected. The automatic mode, as described above, adjusts the gain, processes all channels, and selects a heart rate according to the best figure of merit. In manual mode, the user selects a particular channel and the gain setting for that channel. The user can also invoke an oscilloscope display within this option. The signal corresponding to the selected channel appears on the screen. The heart rate computations continue. The user can also choose to save data from a session into two files. One file contains the sampled waveform from the selected channel (250 Hz sampling rate, 16 bits per sample). The other file contains the computed heart rates, channels, and timing information.

Acoustic unit + ECG unit

In this mode, the fetal heart rate is computed from the acoustic unit as described. In addition, data from a Corremetrics ECG unit is acquired over a serial link. The display format is changed slightly such that the upper panel depicts the acoustic unit and the lower panel shows the results from the ECG unit. Thus only 9 minutes of data can be shown on a single screen. In addition if data is saved, the heart rate file contains the computed heart rate from the two monitors. This feature is envisioned as a method for more precise evaluation of the acoustic monitor.

One channel oscilloscope

This option is used to view a single channel of data in the time-domain. It can be used to initially set-up the monitor and insure that signal levels are properly adjusted, and that there are no other major signal problems with the system.

Seven channel oscilloscope mode

In this mode, all seven signals are simultaneously displayed as a 7-channel oscilloscope. This enables comparisons of the relative signal quality of the various sensors.

ECG unit only

This option is similar to the acoustic unit only (that is, the display screen is the same), except that the data is obtained from the ECG unit. There is no oscilloscope option, since there is no access to the unprocessed ECG waveform.

4. Test results

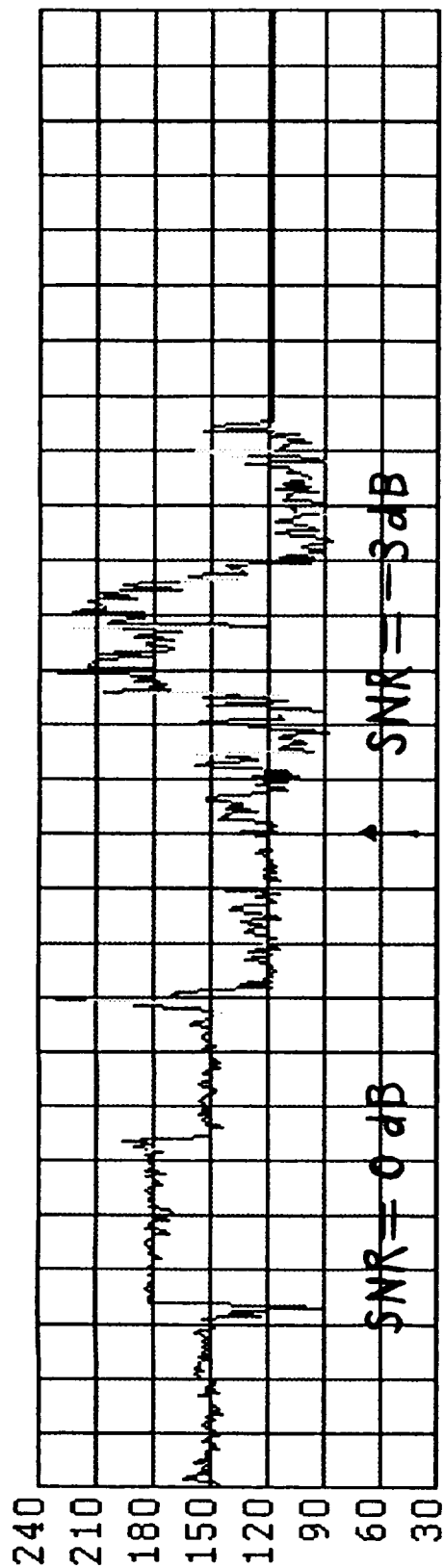
a. Water-filled balloon simulations

For these tests the experimental system developed at NASA was used to simulate a mother and fetus. The acoustic sensor belt was attached to a water-filled balloon internally excited by a vibrator. The signal for the vibrator was a periodic version of one period of a fetal heart waveform obtained from past clinical testing. The repetition frequency was varied from 90 BPM to 210 BPM. Additive white noise could be used to vary the signal to noise ratio. Figures 1 and 2 give tracings from typical tests. The response of the system was found to be accurate over the rate ranges mentioned and for signal to noise ratios up to about 0 dB. For signal-to-noise ratios worse than 0 dB, the system could no longer track the heart rate.

b. Clinical tests

Prior to July 1, 1994, three sets of clinical tests were made, each on three pregnant women. The first two testing sessions resulted in very unsatisfactory results, due to grounding and shielding problems in the system. These problems were corrected, and some algorithmic refinements were added, and a third session was held on June 15, 1994. Results for these sessions are given in Figures 3 through 8. The data show that tracings obtained from the acoustic system are comparable to those obtained with the ultra-sound unit. More complete and thorough testing is, of course, still required.

FETAL HEART RATE



3 gradations/minute

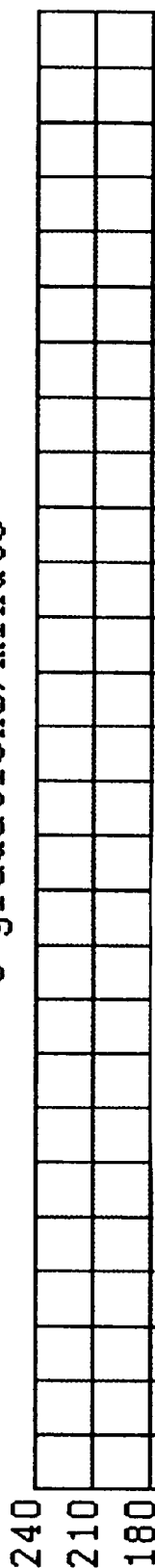


Figure 1. Fetal heart rate tracings obtained from water balloon simulation, with additive noise of either 0 dB (as noted) or -3 dB (as noted), with heart rates of 150, 180, 150, 120 beats per minute. For the 0 dB case, the derived heart rates correspond to the repetition rate of the signal source. For the -3 dB case, the system was unable to track the heart rate.



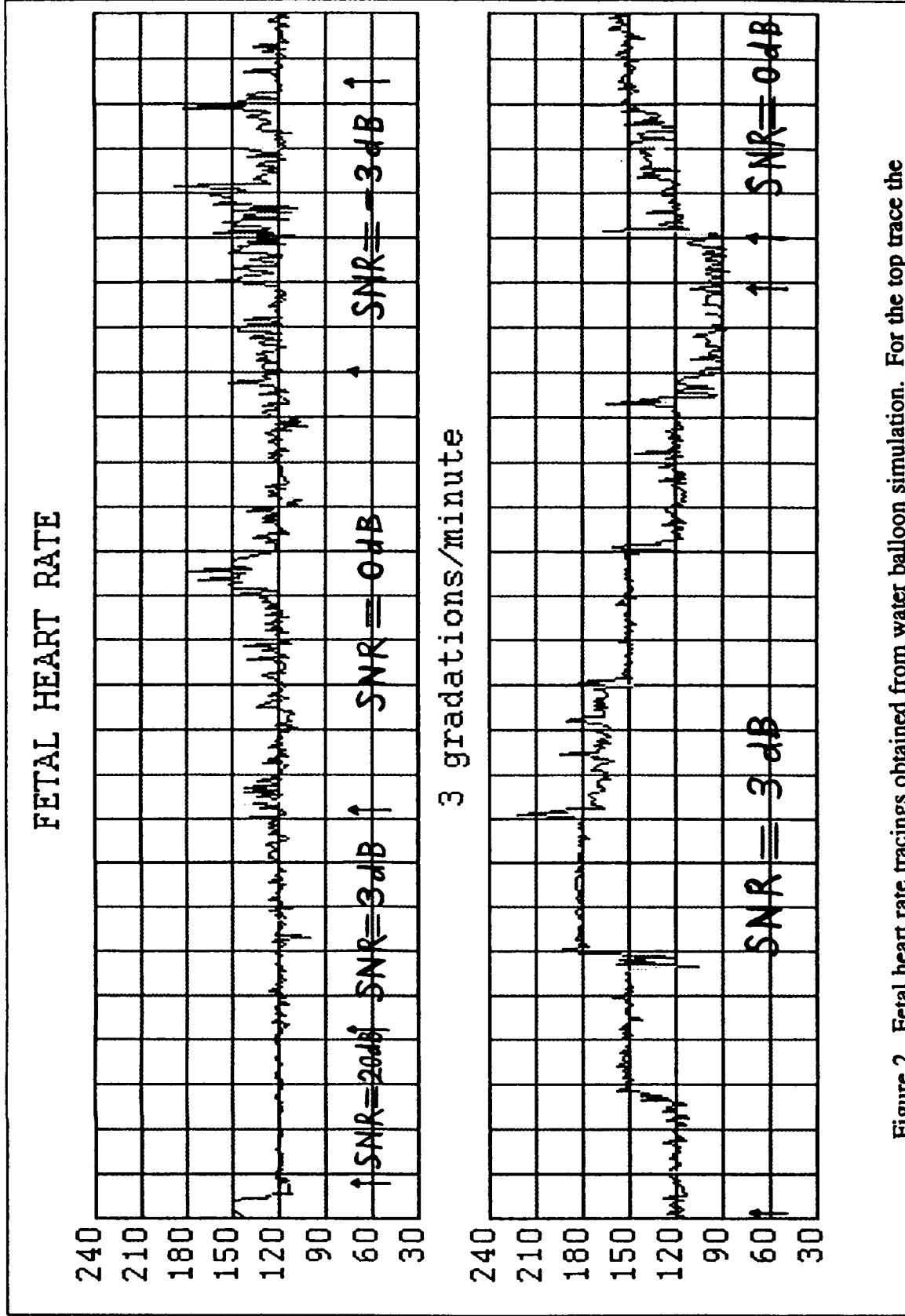
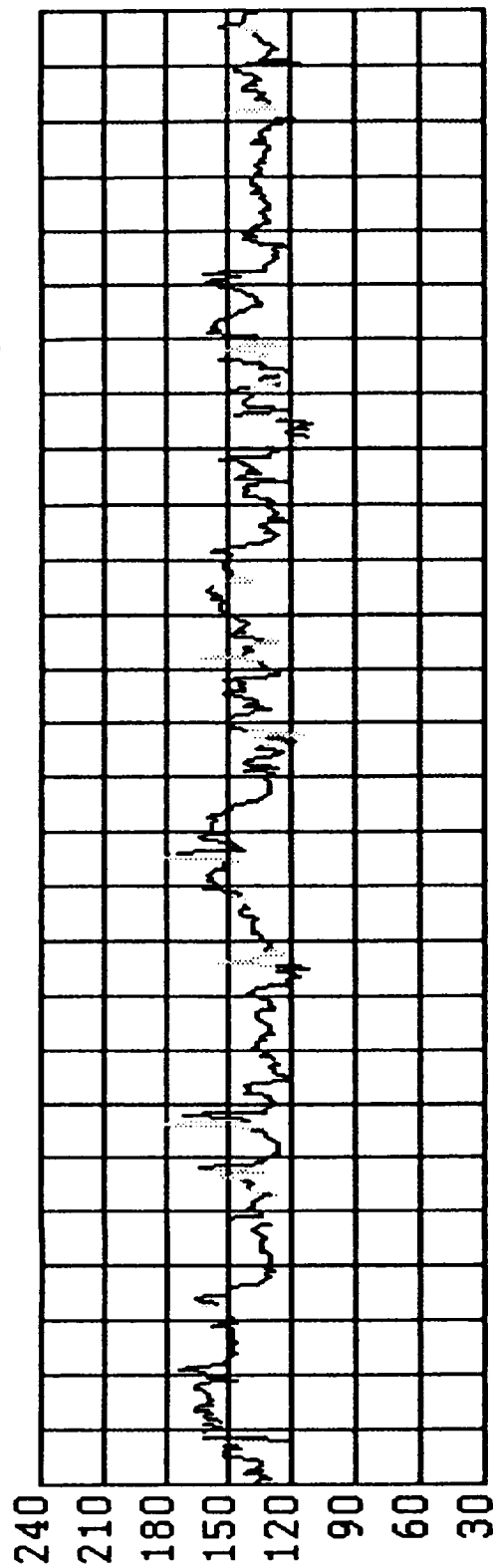


Figure 2. Fetal heart rate tracings obtained from water balloon simulation. For the top trace the source repetition rate was 120 BPM, and the SNR was varied from 20 dB (no added noise) to -3 dB. For the bottom trace the repetition rate was varied and the SNR was either 3 dB or 0 dB. These data demonstrate reliable tracking up to about a SNR of 3 dB.

FETAL HEART RATE



3 gradations/minute

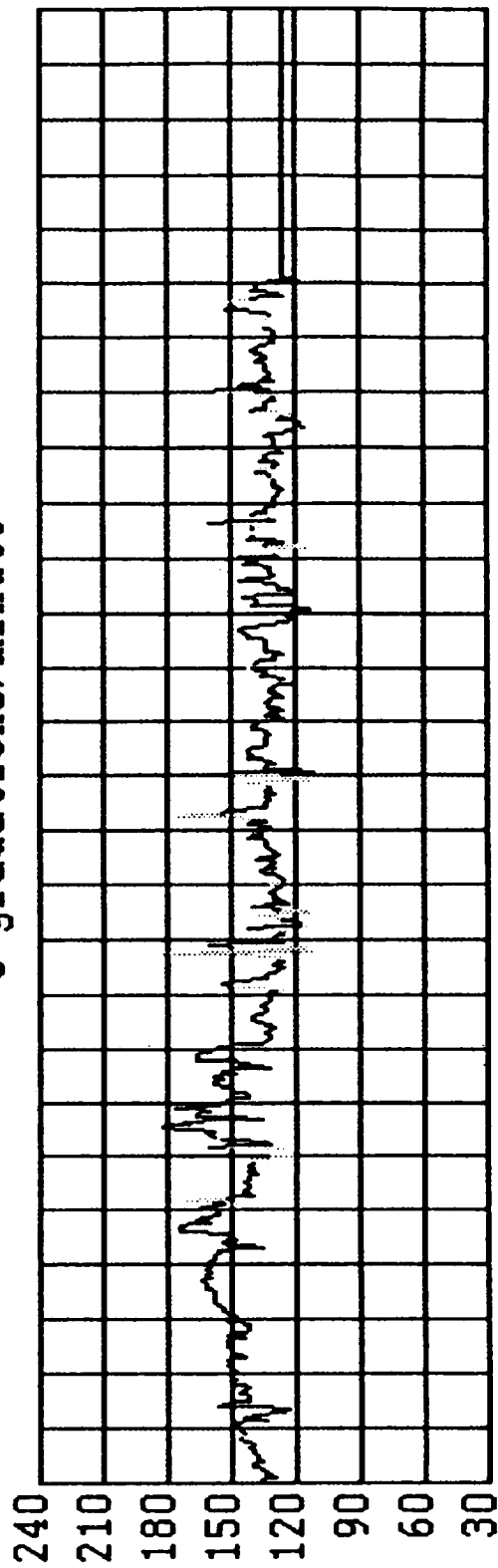


Figure 3. Fetal heart rate tracing obtained from acoustic monitoring, as obtained from patient one on June 15, 1994. Gestation age is 35 weeks.

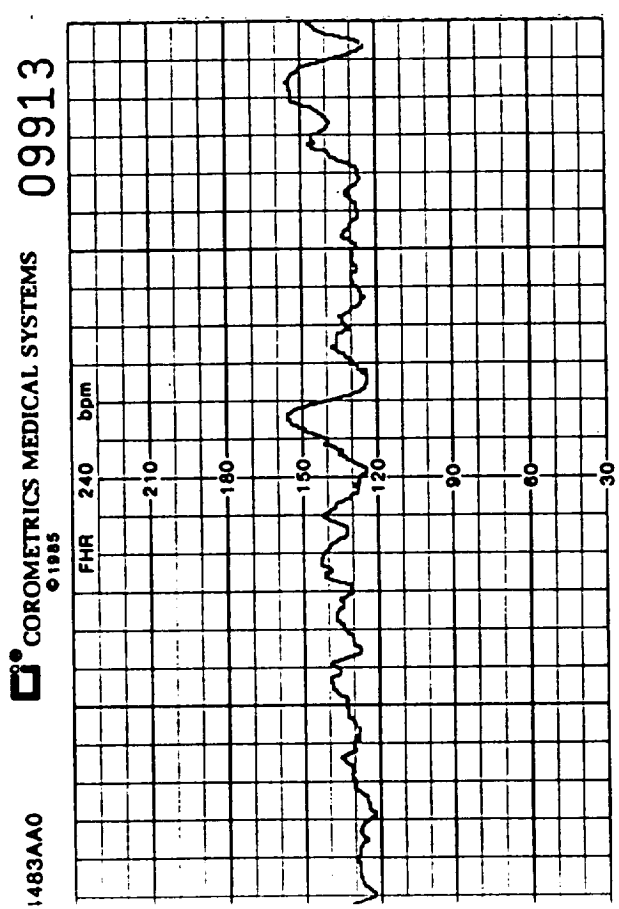
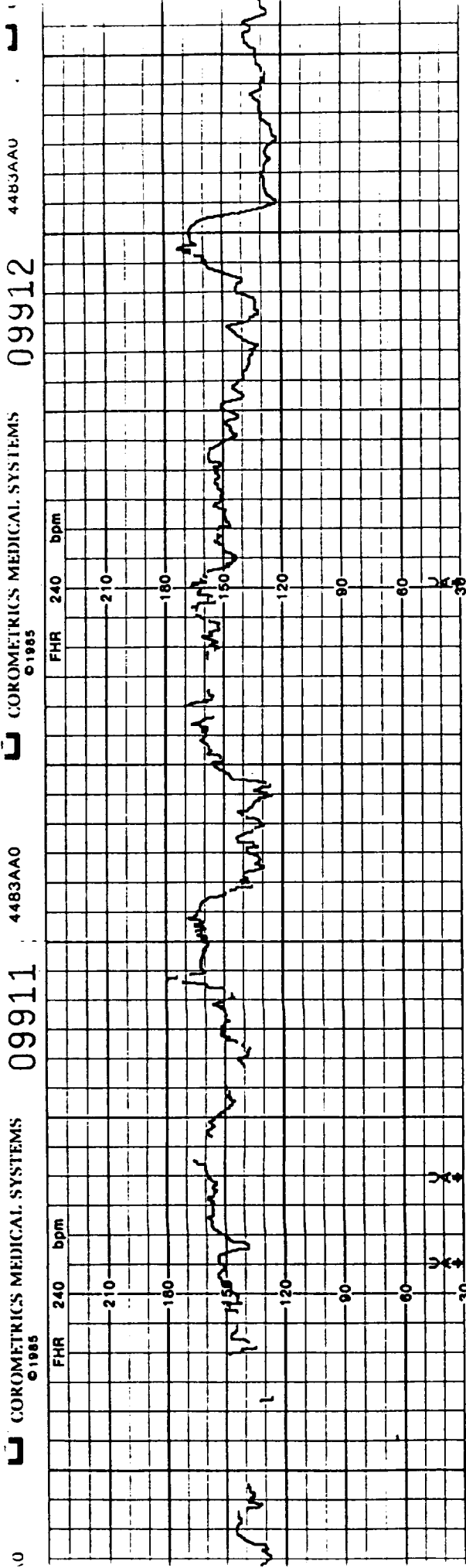
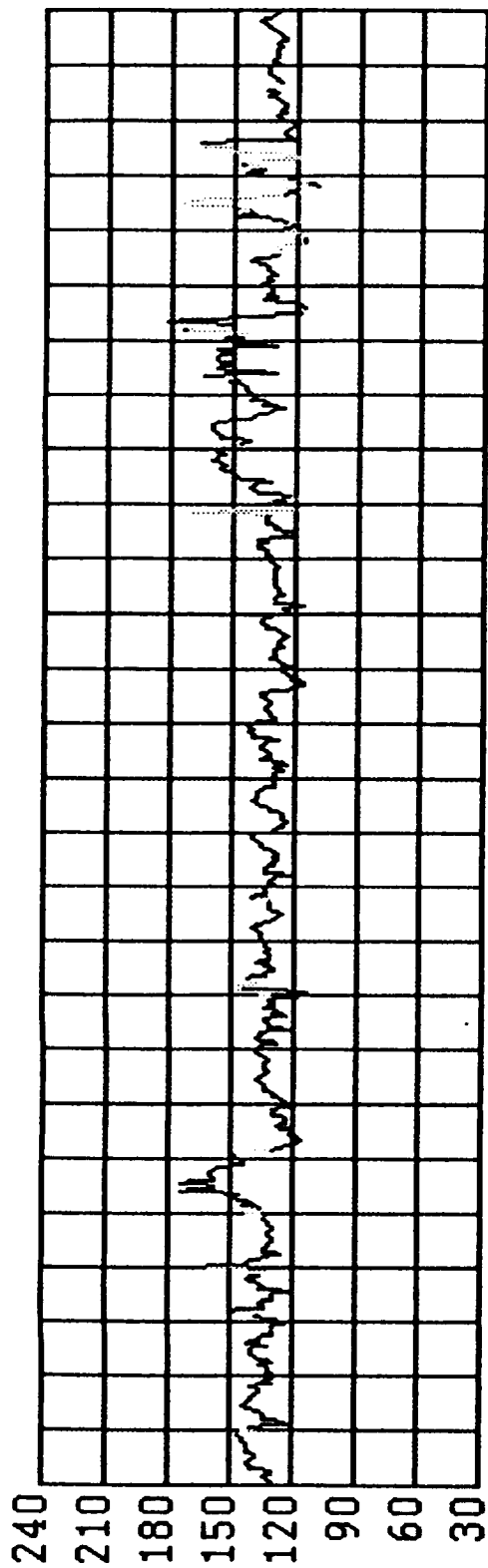


Figure 4. Fetal heart rate tracing obtained from ultrasound monitoring, as obtained from patient one on June 15, 1994. Gestation age is 35 weeks. Note that the tracing was for the same patient as shown in Figure 3, but the tracing was made about 30 minutes before the tracing made with the acoustic unit.

FETAL HEART RATE



3 gradations/minute

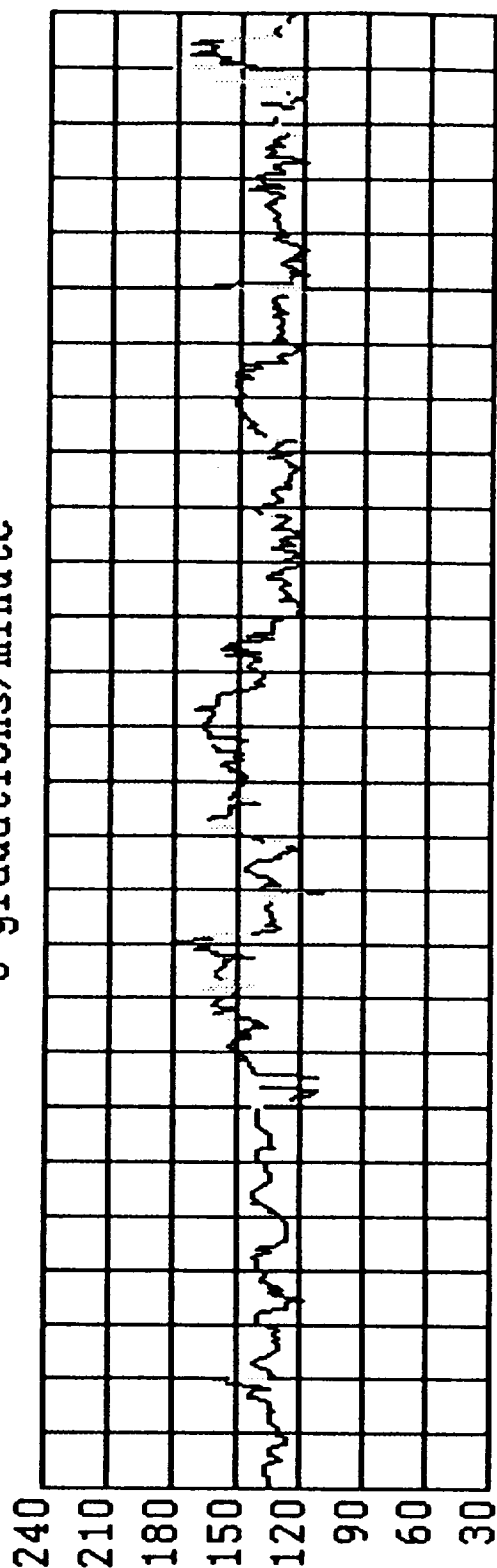


Figure 5. Fetal heart rate tracing obtained from acoustic monitoring, as obtained from patient two on June 15, 1994. Gestation age is 39 weeks.

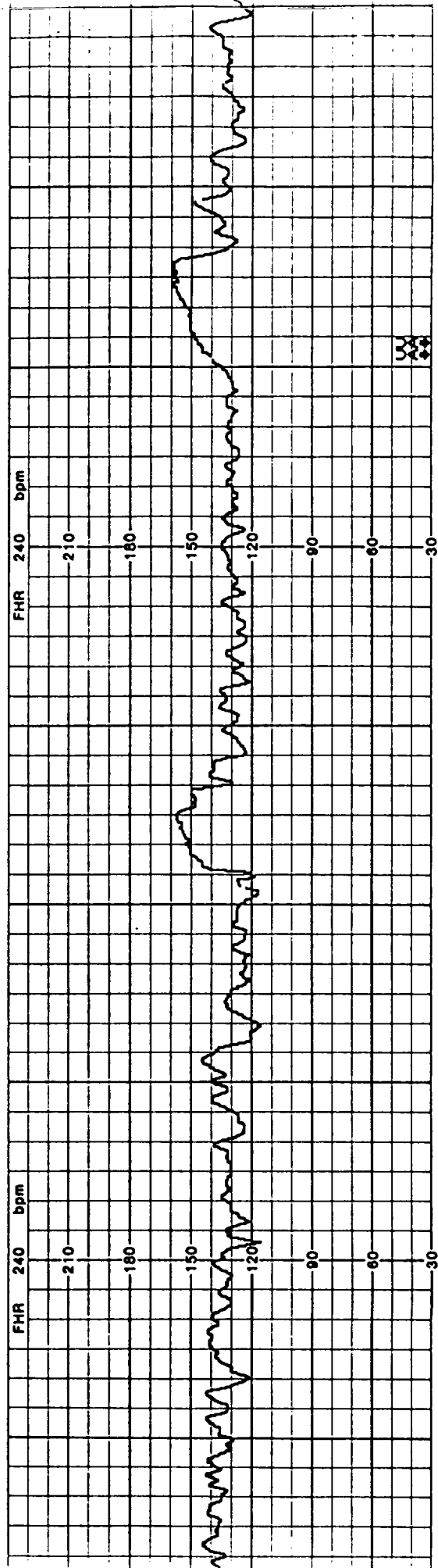
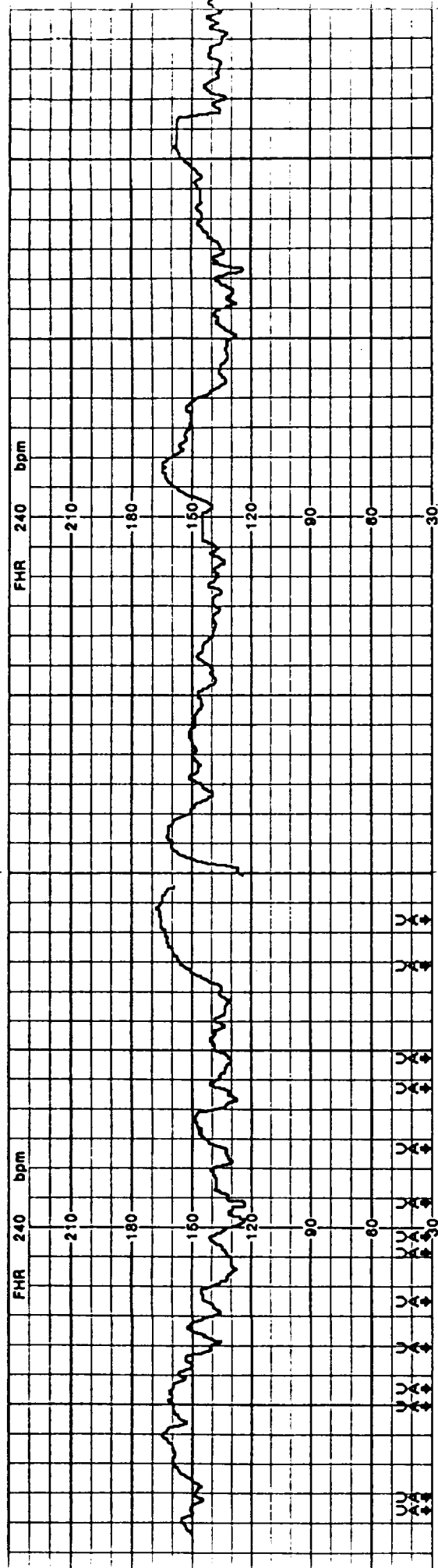


Figure 6. Fetal heart rate tracing obtained from ultrasound monitoring, as obtained from patient three on June 15, 1994. Gestation age is 39 weeks. Note that the tracing was for the same patient as shown in Figure 5, but the tracing was made about 30 minutes before the tracing made with the acoustic unit.

FETAL HEART RATE

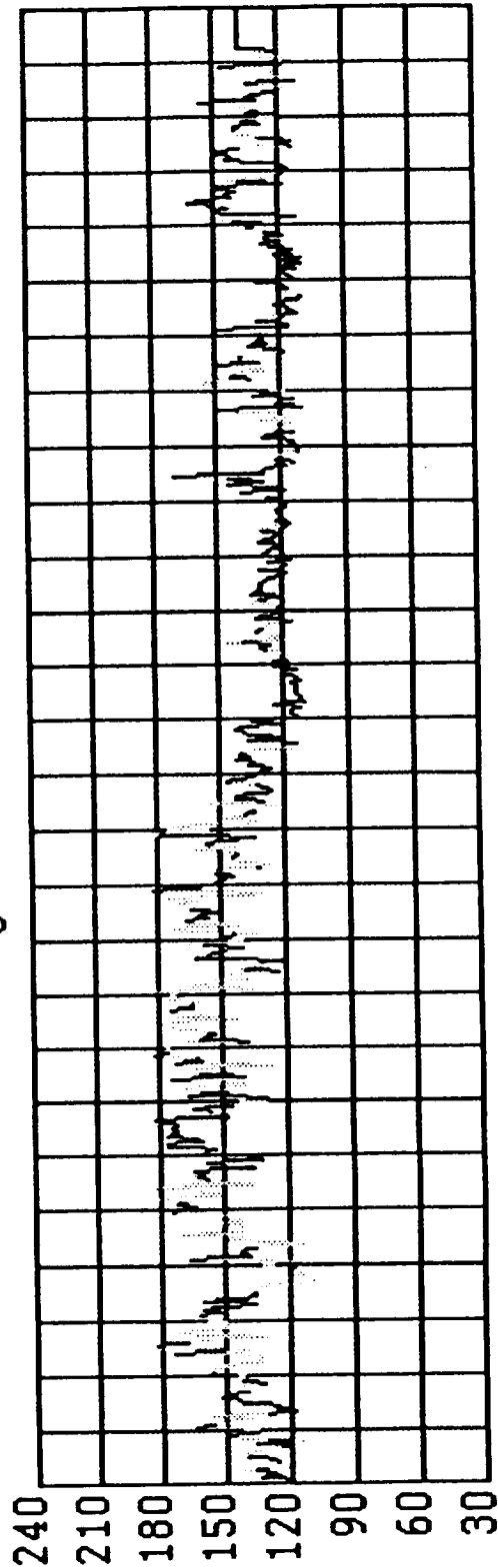
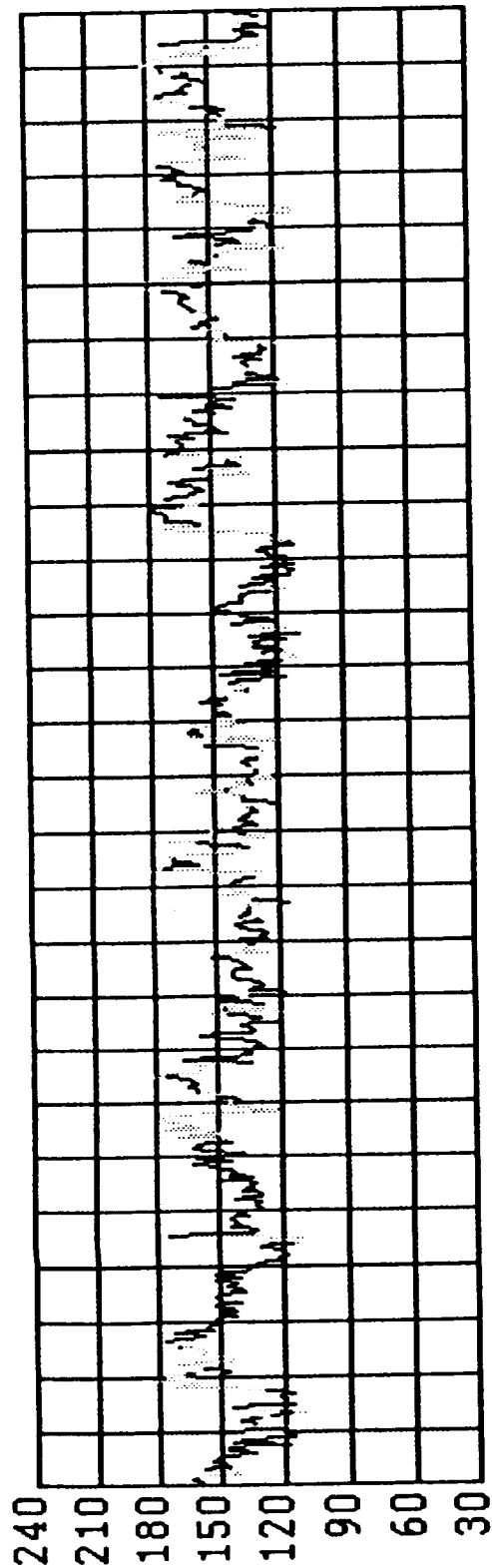


Figure 7. Fetal heart rate tracing obtained from acoustic monitoring, as obtained from patient one on June 15, 1994. Gestation age is 31 weeks.

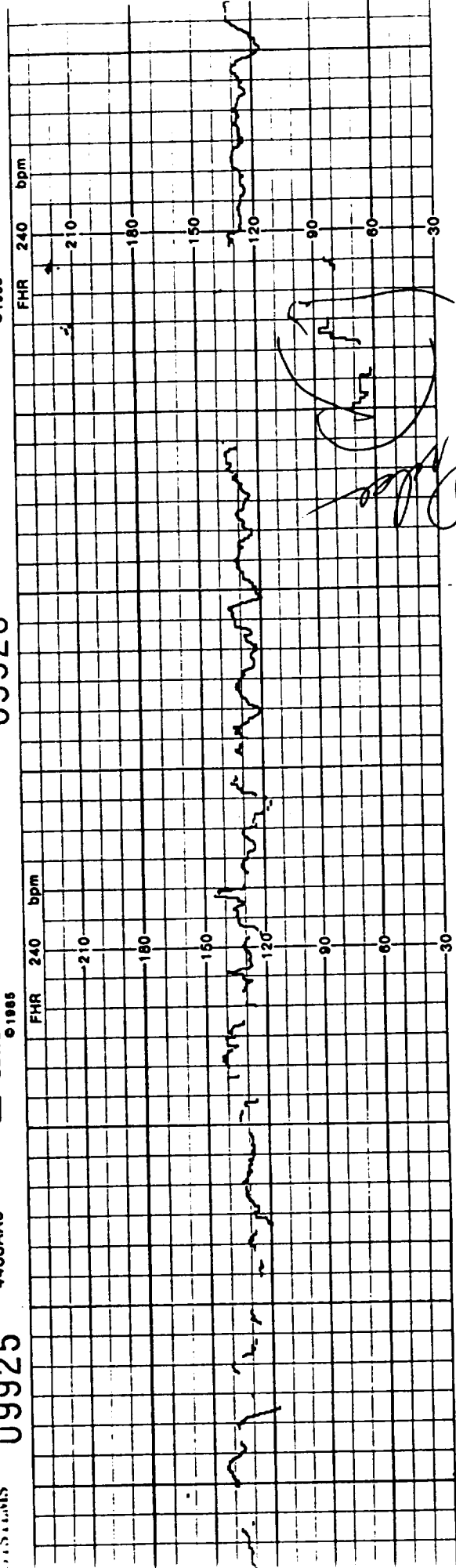
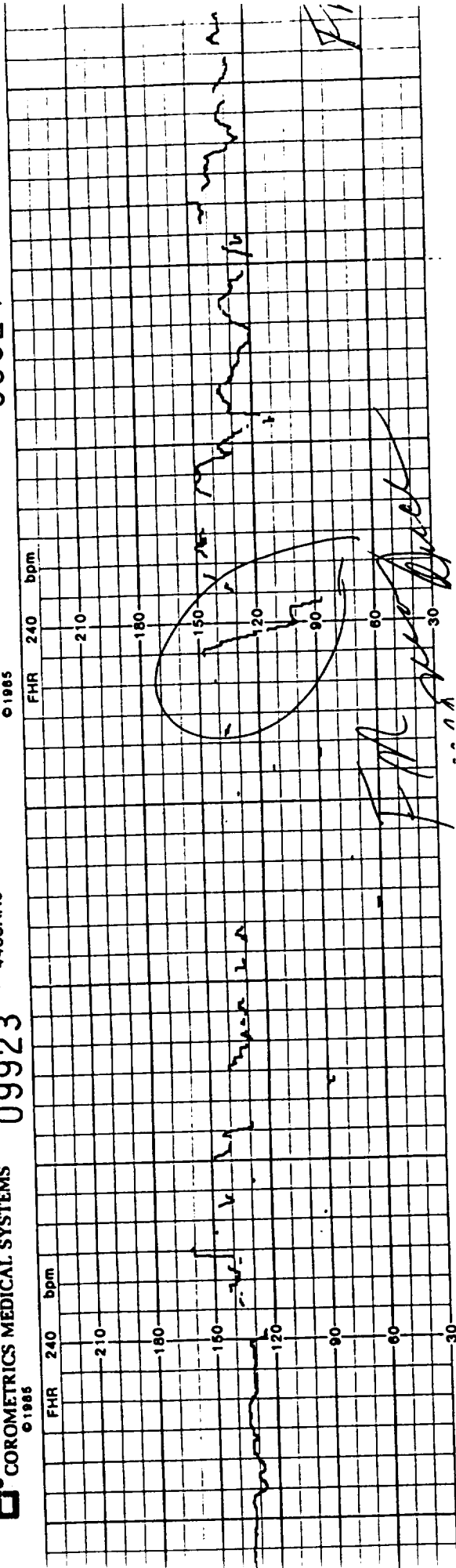


Figure 8. Fetal heart rate tracing obtained from ultrasound monitoring, as obtained from patient three on June 15, 1994. Gestation age is 31 weeks. Note that the tracing was for the same patient as shown in Figure 7, but the tracing was made about 30 minutes before the tracing made with the acoustic unit.